



Calhoun: The NPS Institutional Archive DSpace Repository

Theses and Dissertations

1. Thesis and Dissertation Collection, all items

1953

Variation of burning velocity with pressure

Pardee, William McK.

California Institute of Technology

<http://hdl.handle.net/10945/14763>

Downloaded from NPS Archive: Calhoun



<http://www.nps.edu/library>

Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community.

Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

VARIATION OF BURNING VELOCITY
WITH PRESSURE

WILLIAM MCK. PARDEE

1953

Library
U. S. Naval Postgraduate School
Monterey, California

VARIATION OF BURNING VELOCITY
WITH PRESSURE

Thesis by

William McK. Pardee
Lieutenant Commander, USN

In Partial Fulfillment of the Requirements
For the Degree of
Aeronautical Engineer

California Institute of Technology

Pasadena, California

1953

PIS

ACKNOWLEDGEMENTS

The author is deeply indebted to Mitchell Gilbert for his supervision, help, and patience during the performance of this research; to Dr. F. E. Marble for his suggestions in preparation of the manuscript; and to Rex Shields and Bob Farrel for their expert technical assistance in the maintenance and numerous modifications of the equipment required during the experimental work.

ABSTRACT

A review of some of the recent theories of steady state flame propagation in gaseous mixtures reveals a considerable difference in their prediction of the effect of pressure on burning velocity. Furthermore, the experimental data obtained by various workers in the field indicate widely different trends. In some cases burning velocity appears to be independent of pressure whereas in other cases it appears to increase as the pressure is reduced below atmospheric. Hence, as a possible aid in discovering more about the mechanism of flame propagation, the burning velocity of several gaseous mixtures was studied over the general pressure range from 100 to 700 mm Hg absolute.

The mixtures used were acetylene-oxygen, acetylene-air, acetylene-oxygen-nitrogen, ammonia-oxygen, ammonia-oxygen-nitrogen, carbon monoxide-oxygen, carbon monoxide-air, and propane-air. Using the burner-visual cone-area method with burners of various sizes, the following results were obtained: for all the above mixtures, except propane-air, the burning velocity is independent of pressure; for propane-air mixtures, the burning velocity varies as $P^{-0.13}$. These results are valid provided the burner size is large enough to nullify the effect of quenching.

It is concluded that these results definitely do not support the Tanford and Pease theory that burning velocity varies as $P^{-0.25}$.

TABLE OF CONTENTS

<u>PART</u>	<u>TITLE</u>	<u>PAGE</u>
I	Introduction	1
II	Equipment	7
III	Experimental Procedure	10
IV	Discussion of Results	13
V	Concluding Remarks	21
	References	22
	Tables	25
	Figures	26

I. INTRODUCTION

Burning velocity, sometimes called normal or fundamental flame speed, is defined as the linear velocity, normal to the flame front, relative to the velocity of the unburned gas entering the combustion zone. Determinations of the burning velocities of gaseous mixtures have been made by many workers. Various methods have been employed, discussions of which are contained in the works of various authors, for example Jost⁽¹⁾, Lewis and von Elbe⁽²⁾. These methods include the Bunsen flame method, the soap bubble method, the flame tube method, the spherical bomb method, the flat flame method, and others. Since the first two mentioned methods are widely used at present to study the effect of pressure on flame speed, they will be described briefly.

The Bunsen burner method of obtaining burning velocities depends upon observing an inner cone of the flame, this cone representing a reference flame front or ignition boundary. Then, using either a modification of the Michelson cone-apex angle method^(1, 2, 3) or of the Gouy cone-area method^(1, 2, 4), the burning velocity is computed. The inner cone of a Bunsen flame has been determined by direct, schlieren, and shadow photography. For hydrocarbon combustion flames, however, as pointed out by Linnett⁽⁵⁾, the three cones thus determined generally do not coincide. It is readily apparent, therefore, that the value of burning velocity determined for a given mixture may be found to vary slightly, depending on which inner cone is used.

The procedure of the soap bubble method was devised by Stevens^(1, 2, 6). A soap bubble is filled with the desired gas mixture

which is ignited by a spark at the center. By measuring the speed of the flame through the expanding gas and correcting for the gas movement during the burning of the bubble, the burning velocity can be obtained. Linnett and his co-workers^(7,8) have developed this method so that burning velocity can be determined at pressures different from atmospheric, and have substituted schlieren photography for direct photography.

Linnett⁽⁹⁾ and other researchers have pointed out that the various methods give different absolute values of burning velocity for a particular gaseous mixture; however, the primary requirement for this present investigation is that the method employed be adequate to give the variation of burning velocity with pressure. The method must also give results for burning velocity in reasonable agreement with other techniques.

Considerable interest has been shown recently in the variation of the burning velocity of gaseous mixtures with pressure because such observations may lead to a better understanding of the mechanism of flame propagation. In fact, the various current theoretical concepts of steady state flame propagation make different predictions regarding the effect of pressure on burning velocity. Thus, Tanford and Pease⁽¹⁰⁾ have proposed that burning velocity should vary inversely as the fourth root of pressure; Gaydon and Wolfhard⁽¹¹⁾, that burning velocity should be independent of pressure; Boys and Corner⁽¹²⁾, Zeldovich, Frank-Kamenetski⁽¹³⁾, Hirschfelder and Curtiss^(14,15), that burning velocity should have a pressure dependence related with chemical kinetics. For example, for a unimolecular reaction, the

burning velocity should vary inversely as the square root of pressure; for a bimolecular reaction, the burning velocity should be independent of pressure.

Experimental results have also shown a variety of trends; in some cases burning velocity appears to change as the pressure is lowered below atmospheric, while in others the burning velocity appears to be unaffected by pressure changes.

Thus, Cullen⁽¹⁶⁾ observed the effect of pressure on the burning velocity of propane-air and ethylene-air mixtures, using the cone-area method and direct photography for various sizes of burners at pressures from atmospheric to 25 mm Hg absolute. He concluded that burning velocity decreases as the logarithm of pressure for both propane-air and ethylene-air within this range of pressures, if the burner diameters were chosen large enough. Although Cullen pointed out that his results for propane-air agree reasonably well with the conclusions of Tanford and Pease that burning velocity should vary as $P^{-0.25}$, it is shown later in this report that both his propane-air and ethylene-air data can be more precisely interpreted as disagreeing with this Tanford and Pease theory.

Culshaw and Garside⁽¹⁷⁾ obtained data for ethylene-air, carbon monoxide-air, and propane-air mixtures over a range of pressures from atmospheric to 200 mm Hg absolute. Their data show no definite trends of burning velocity with pressure.

Pickering and Linnett⁽¹⁸⁾ studied the effect of pressure on the burning velocity of some ethylene-air mixtures using the soap bubble method and schlieren photography. They found that the burning velocity remained constant over the pressure range 200 to 760 mm Hg absolute.

Ubbelohde⁽¹⁹⁾ observed that burning velocities of carbon monoxide-air mixtures increased with decreasing pressure down to a pressure of 330 mm Hg absolute. At lower pressures he observed a sharp reduction in the burning velocities. Gilbert⁽²⁰⁾ found that the burning velocity for several carbon monoxide-oxygen flames using flat and nearly flat flames was not significantly affected by pressure.

Wolfhard⁽²¹⁾ observed flames burning at pressures as low as 5 mm Hg absolute. His conclusions were that burning velocity for a stoichiometric mixture of acetylene-oxygen was independent of pressure, although the data for extremely low pressures indicated a decrease of burning velocity. In these experiments Wolfhard found that tubes of larger diameter were necessary to continue to decrease the pressure while maintaining stable flames. Gilbert⁽²⁰⁾ and Eriksen⁽²²⁾ have likewise observed similar results.

Eriksen⁽²²⁾, using the visual cone-area method, noted that his data for acetylene-oxygen and propane-oxygen flames at pressures from 5 to 100 mm Hg absolute definitely did not support the theory of Tanford and Pease. Rather his work supported the conclusions of Gaydon, Wolfhard, and Gilbert, that burning velocity is independent of pressure, with the qualification that at low pressures, a pressure dependent quenching effect predominates. His results for the combustion processes studied were also shown to agree with the theoretical work of Boys and Corner⁽¹²⁾ based on a bimolecular reaction.

A logical explanation for the decrease of burning velocity at very low pressures, both with decreasing pressure and with decreasing

burner diameter, as noted by Cullen⁽¹⁶⁾, Gilbert⁽²⁰⁾, Wolfhard⁽²¹⁾, and Eriksen⁽²²⁾, lies in the phenomenon of quenching. Thus, the relatively cool duct rim acts as a sink for heat and probably for chain carriers due to the adsorption of atoms and free radicals. It follows, therefore, that conditions tending to maximize this effect are very low pressures, small gas flows, and small burner ducts. More detailed treatments of quenching and its effects, particularly with regard to flame stability, have been covered by Lewis, von Elbe, and their co-workers⁽²⁾. Cullen⁽¹⁶⁾ presents an interesting treatment of the quenching effect on flame speed based on the Peclet number, which qualitatively, at least, accounts for many of the observed data.

Wheatley and Linnett⁽²³⁾, using the soap bubble direct photography method, studied the effect of pressure from 200 to 760 mm Hg absolute on the burning velocities of (a) 10 volume percent acetylene plus oxygen and nitrogen and (b) 10 volume percent acetylene plus oxygen and argon, the proportion of oxygen to inert gas being 1 to 3.76 in each case. The results indicated the burning velocity to be constant for both mixtures within the limits of measurement.

Badin, Stuart, and Pease⁽²⁴⁾ found that for butadiene-oxygen-inert gas flames, the burning velocity increased as the pressure was reduced below atmospheric. The value passed through a maximum, but this trend may well have been due to the quenching effect of the burner rim.

Friedman and Burke⁽²⁵⁾ studied an ethylene oxide decomposition flame by means of a flat flame burner. Over a pressure range from 350 to 1130 mm Hg absolute they found that the burning velocity

varied inversely as the fourth root of pressure, thus agreeing with the Tanford and Pease theory. According to the theory of Hirschfelder and Curtiss^(14, 15), however, for a first order reaction, the burning velocity should vary inversely as the square root of pressure. Although data exist supporting a first order reaction for the homogeneous ethylene oxide decomposition, there is as yet no proof of this for a flame.

It is seen, then, that the results fall into two groups. In some cases they indicate that the burning velocity increases as the pressure is lowered below atmospheric, while in others they indicate that the burning velocity is unaffected by change of pressure. It is difficult to say whether this difference in behavior is real or whether it is the result of some inconsistencies inherent in the methods used. It follows, therefore, because of theoretical interest and experimental uncertainty that further studies of burning velocity are of considerable importance. For these reasons, the following investigation has been made of the effect of pressure on the burning velocity of various fuel gases, namely, acetylene-oxygen, acetylene-air, acetylene-oxygen-nitrogen, ammonia-oxygen, ammonia-oxygen-nitrogen, carbon monoxide-oxygen, carbon monoxide-air, and propane-air.

II. EQUIPMENT

The apparatus used in this investigation, including the combustion chamber, pumping system, and flow system, has been described in detail by Gilbert⁽²⁰⁾. Briefly, the equipment (Figure 1) consists of a double-windowed combustion chamber, 24 inch inside diameter and 60 inch height; a vacuum system employing a Kinney model DVD 1414818 mechanical vacuum pump, an acoustic filter; and a two-stage pressure regulated flow system with Fischer-Porter C-clamp calibrated Flowrators (rotameters) measuring the volume flow. The accuracy of these meters was checked against a Precision Wet-Test Gas Meter and found to lie within $\pm 2\%$ over the range of flow generally required in the experiments. The pressure in the combustion chamber is controlled by means of a bleed valve which allows a constant leak of atmospheric air into the acoustic filter. With the bleed-air entering far downstream and close to the pump suction, no appreciable dilution can occur in the exhaust gas atmosphere surrounding the flame. A single tube mercury manometer fitted with an adjustable millimeter scale is used to measure pressures above 100 mm Hg absolute with a maximum error of 0.5 mm.

Bottle supply gases of commercial purity (Table I) are used. The gas flows are metered at a constant pressure of 40 psia through the rotameters, controlled by long taper needle valves downstream from the meters, mixed in a mixing chamber, and thence are led into a circular inlet duct. At this point a honey-comb filter acts to suppress disturbances created in the mixing chamber and to produce a uniform velocity. The burner duct length is then sufficient to allow

the building up of the parabolic velocity profile, characteristic of fully developed laminar pipe flow, by the time the burner duct exit is reached. The duct exit (Figure 2) is contained in an annular water-cooled chamber and is flush with its flat upper surface. This arrangement serves to prevent excessive heating at the exit, to assure a constant temperature surface when quenching effects are considered, and to act as a flat plane baffle in regard to diffusion of the chamber atmosphere into the flame.

Additional equipment required by this investigation is an optical system for obtaining an image of the flame. This system consists of a 5 inch diameter double-convex lens mounted outside one chamber window, and a pedestal-mounted glass plate which, covered with a thin transparent plastic, acts as a screen for the flame image. A front surface plane mirror mounted at 45° erects and projects the flame image to a horizontal plane. The system is adjusted so as to obtain a full scale image to an accuracy of about 1%. The flame profile may then be traced in a few seconds. A cathetometer mounted outside the opposite chamber window is used to check the accuracy of the traced flame height.

Burners of various diameters are employed in order to cover a wide pressure range of stable burning for a particular gas mixture. Thus, at the higher range of pressures and consequently high volume flows, smaller burners serve to prevent turbulence due to Reynolds number; at lower pressures and low volume flows, larger burners serve to minimize quenching effects. The burners include inlet ducts of 2.32, 1.86, 1.25, 0.873, 0.500 inch diameter, and, to increase the flexibility of the system, long nozzle inserts of 1.00 and 0.685 inch

inside diameter. The larger insert is used with the 1.25 inch duct; the smaller one with the 0.873 inch duct.

The inserts (Figure 2) are approximately 1.5 diameters in length, machined to fit snugly into the exit end of their respective ducts, their inner bore being gradually tapered from their maximum diameter at their upstream end to their final cylinder diameter at about their mid-length. The effect of the inserts on the gas flow was apparently to flatten the velocity profile somewhat, as evidenced by the straighter sides of the flame cones observed burning on the inserts.

III. EXPERIMENTAL PROCEDURE

The procedure followed in obtaining data for burning velocity in this investigation was essentially the same as that used by Gilbert⁽²⁰⁾ and Eriksen⁽²²⁾. After establishing a stable flame on the duct at the desired chamber pressure, the flame profile was traced and the following data were recorded: the chamber pressure in mm Hg absolute, the flowrator readings, and the flame height obtained by the cathetometer. The flame profile traced was the upstream boundary of the luminous cone (Figure 2). For the gas mixtures used over the range of pressure considered, this cone was generally sharp and well defined. The height measured by the cathetometer was the height of this cone, not including the dead space, i.e., the vertical distance between the top of the burner lips and the base of the flame. Readings were taken at pressure increments of about 25 mm Hg over the pressure range from 100 mm Hg absolute to atmospheric pressure (or as limited by flame stability), maintaining a constant mixture ratio.

For mixtures in which the fuel gas was ammonia or carbon monoxide, an acetylene-oxygen flame was first established at a pressure of about 20 mm Hg absolute. Then, while the chamber pressure was raised, the NH₃ (or CO) was introduced, and the C₂H₂ flow was gradually reduced. At some elevated pressure a stable flame could be obtained with the desired fuel mixture, the C₂H₂ flow being eliminated entirely.

In reducing the data, burning velocity was calculated following the Gouy total area method^(1, 2, 4). Thus, burning velocity was obtained by dividing the volume flow of the incoming gases (corrected to the

chamber pressure) by the flame area. The volumetric flow in the duct was determined from the metered flow, which was converted by the rotameter calibration curves to standard cc/min (70°F , 760 mm Hg abs.). For the inlet condition, temperature was assumed constant (room temperature); hence, this standard volume flow was corrected to chamber pressure by Boyles Law. The flame area was obtained by approximating the flame image to one or more surfaces of revolution. In general, the inner cone trace was found to be closely approximated by a hemispherical cap for the apex of the flame, and two or more right circular cone frustums for the remainder of the flame (Figure 2). The accurate absolute cone height measured by the cathetometer served as a check for the traced cone height.

The following simple development provides the basis for the reduction of experimental data:

For $p_1 = 760$ mm Hg abs.

V_1 = total std. metered volume flow

p_2 = chamber pressure, mm Hg abs.

V_2 = total volume flow at chamber pressure

U_2 = burning velocity

A_2 = area of flame front (inner cone)

Then from the Continuity Equation and the Perfect Gas Law for constant temperature

$$p_1 V_1 = p_2 U_2 A_2$$

or
$$U_2 = \frac{V_1}{A_2} \frac{p_1}{p_2} = \frac{V_1}{A_2} \frac{760}{p_2}$$

By definition, mixture ratio = $\frac{\text{vol. flow of fuel gas}}{\text{vol. flow of O}_2(\text{or O}_2+\text{N}_2)}$.

The overall measurement accuracy for this procedure is considered to be of the order of ± 3%.

IV. DISCUSSION OF RESULTS

The results are presented as plots of burning velocity in fps versus pressure in mm Hg absolute. Figure 3 shows the results for an acetylene-oxygen mixture ($\frac{C_2H_2}{O_2} = 0.056$ volume or mole ratio). It is seen that for the pressure range from 50 to 375 mm Hg absolute the effect of pressure on burning velocity is negligible within the limits of experimental accuracy. The average value of burning velocity for this mixture agrees very closely with that of Eriksen⁽²²⁾ whose work covered the pressure range from 5 to 100 mm Hg absolute.

In order to obtain data for C_2H_2 flames in the high pressure range, it was necessary to use slow burning rich or lean mixtures to avoid the effects of turbulence which began to cause flame distortion and flickering at Reynolds numbers above 500. In fact, even with the relatively slow burning mixture ratio of 0.056, flame turbulence precluded laminar flame study above a pressure of 400 mm Hg absolute.

The results for the acetylene-air mixtures are indicated in Figures 4 and 5. For three volumetric mixture ratios ($\frac{C_2H_2}{air} = 0.05$, 0.08, 0.1755), Figure 4 shows no effect of pressure on burning velocity. These results are in accord with those obtained by Linnett and co-workers⁽²³⁾. For a mixture of C_2H_2 -air containing 10 volume percent C_2H_2 (corresponding to $\frac{C_2H_2}{air} = 0.111$), using the soap bubble method, they found the burning velocity to be essentially constant from 200 to 760 mm Hg absolute. In Figure 5, a plot of burning velocity versus mixture ratio for a constant pressure of 250 mm Hg

absolute, the comparison may be carried further. Thus, Linnett's data give an average value of 4.8 fps for the burning velocity of this mixture compared to the corresponding value of 5.1 fps from the curve in Figure 5 for this investigation, a difference of about 6%.

Another interesting comparison can be made with the data for acetylene-air obtained by the burner method at atmospheric pressure by F. A. Smith (as reproduced in Ref. 7). In Figure 5, the close agreement of his data and the data of this report, obtained at a pressure differing by about 500 mm Hg, tends to indicate the improbability of any significant effect of pressure on burning velocity for acetylene-air mixtures.

A variation of the acetylene-air experiment was performed by adding an inert diluent gas, nitrogen. The volumetric ratio of nitrogen to oxygen was made 6 to 1, and an overall volumetric mixture ratio, $\frac{C_2H_2}{O_2 + N_2}$, of 0.08 was maintained. The results for this composition are shown in Figure 6. Again, the results indicate no effect of pressure on burning velocity within experimental accuracy.

In order to acquire a reasonably conclusive amount of data over the desired pressure range for this phase of the investigation, it was necessary to use larger size ducts at the lower pressures. Thus, in addition to the 0.5 inch duct, the 1.25 inch duct and the 0.685 inch insert were employed. As pointed out in the Introduction of this report, such a requirement can be attributed to the phenomenon of quenching, produced by the conditions of low pressure, small gas flow, and small duct size.

This experiment also served to emphasize the care required

to obtain a constant, steady mixture ratio for a three component mixture. A study of the data indicated that the relatively wide scatter of some of the points in Figure 6 could be accounted for by inconsistencies of mixture ratio due to metering in the less accurate portions of the rotameters. The data obtained with the 0.5 inch duct for this gas mixture, for example, were so widely scattered that they were considered unreliable and were not included in Figure 6. This scatter of data is probably a result of quenching, variable mixture ratio, and the accentuation of flame area errors on a small duct.

As an example of a non-hydrocarbon fuel, ammonia was burned with oxygen and with oxygen plus nitrogen. For $\text{NH}_3\text{-O}_2$ mixtures ($\frac{\text{NH}_3}{\text{O}_2} = 0.5$ and 1.15 volume ratio) the results are shown in Figure 7. Over the pressure range from 75 to 385 mm Hg absolute, the effect of pressure on burning velocity is seen to be insignificant. A comparison of the average values of burning velocity of these mixtures with the corresponding values by Ausloos and Van Tiggelen⁽²⁶⁾, obtained by a cone-area method with photography at atmospheric pressure, shows the results of this report to be about 10% greater for both mixtures. This disparity may be explained by a consideration of the nature of the $\text{NH}_3\text{-O}_2$ flame. The inner cone of this flame is more diffuse and not as sharply defined at low pressures as is the inner cone of the $\text{C}_2\text{H}_2\text{-O}_2$ flame. Thus, for the $\text{NH}_3\text{-O}_2$ flame, the trace or photograph of the inner cone is more subject to personal choice. Also, the relatively great dead space for these flames at low pressures, allowing leakage of the unburned gas mixture between the

rim of the duct and the base of the flame, tends to give a smaller flame area for the measured gas flow and correspondingly a larger burning velocity. Also Ausloos and Van Tiggelen used an empirical area measurement that would account for about 3% of the difference. Regardless of these possible sources of disagreement, however, this comparison indicates an insignificant effect of pressure on the burning velocity of $\text{NH}_3\text{-O}_2$ mixtures.

A similar comparison for $\text{NH}_3\text{-O}_2\text{-N}_2$ mixtures is indicated in Figure 8. For this test, carried out at 100 mm Hg absolute, the ratio $\frac{\text{NH}_3}{\text{O}_2} = 1.15$ was maintained, corresponding to the fastest burning mixture reported by Ausloos and Van Tiggelen⁽²⁶⁾, and the volumetric percentage of N_2 was varied from zero to 17%. It is seen from Figure 8 that addition of N_2 acts to decrease linearly the burning velocity of the constant $\text{NH}_3\text{-O}_2$ mixture. These results agree closely with those of Ausloos and Van Tiggelen obtained at atmospheric pressure, particularly with increasing percentage of nitrogen. Again, the results can be interpreted to mean that burning velocity is independent of pressure for $\text{NH}_3\text{-O}_2\text{-N}_2$ mixtures within the limits of experimental accuracy.

As another example of a non-hydrocarbon fuel, this one, however, containing no combined hydrogen, carbon monoxide was burned both with oxygen and with air. The CO-O_2 flame, having a mixture ratio corresponding to 88.9% CO by volume, was studied over the pressure range from 100 to 500 mm Hg absolute, using both a 0.873 inch diameter duct and a 0.685 inch diameter insert. This very rich mixture was used because leaner mixtures emitted such an intense chalk-white light that it was exceedingly difficult,

even with the aid of various filters, to obtain an accurate trace of the inner flame cone. For the CO-air mixture, corresponding to 50% CO by volume, using a 1.25 inch diameter duct, and inserts of 1.00 and 0.685 inch diameter, the burning velocity was obtained for pressures from 200 to 700 mm Hg absolute.

The results, shown in Figure 9, indicate that for both CO-O₂ and CO-air, the burning velocity is independent of pressure, provided the burner diameter be chosen large enough to nullify the effect of quenching. For CO-O₂ these findings agree with the preliminary ones of Gilbert⁽²⁰⁾; for CO-air, the results do not agree with those of Ubbelohde⁽¹⁹⁾. The latter reported an increase of burning velocity as the pressure was decreased from atmospheric to 330 mm Hg absolute, then a sharp decrease of burning velocity for a further reduction of pressure. In Figure 9, the CO-air data do show a very gradual and small reduction of burning velocity as the pressure is reduced below 400 mm Hg absolute; however, such a decrease of burning velocity with pressure at low pressures is attributed to the effect of quenching. For the CO-air data, the dashed straight line thus represents the locus of points unaffected by quenching. The disagreement with Ubbelohde's data may lie in the fact that he chose the flame height as the sole index of cone area.

The carbon monoxide results are further compared with Jahn's data (as reproduced in Ref. 2), obtained by a burner-area method. Figure 9 indicates four values of burning velocity for mixtures of carbon monoxide, oxygen, nitrogen, and water vapor, with and without hydrogen, as taken from Jahn's curves at atmospheric

pressure. Since none of the mixtures for the two reports are exactly the same, the results are compared qualitatively only. From the respective mixture compositions as listed in Figure 9, it is seen that Jahn's data indicate the effect of hydrogen on the burning velocity, keeping the percentage of water vapor constant; and the data of this report together with Jahn's indicate the effect of water vapor on the burning velocity, keeping the percentage of hydrogen approximately constant. Thus, addition of water vapor as well as addition of hydrogen increases the burning velocity of the mixture for both CO-O₂ and CO-air.

The flame of a propane-air mixture, corresponding to 4.21% C₃H₈ by volume, was studied over the pressure range from 48 to 680 mm Hg absolute. Several sizes of burners were used, namely, ducts of 2.32, 1.86, 1.25, and 0.873 inch diameter, and inserts of 1.00 and 0.685 inch diameter. From the results shown in Figure 10 plotted to logarithmic scales, it is immediately apparent that the burning velocity in this case has an inverse pressure dependence.

The relatively great effect of quenching is also indicated by the data. Thus, for pressures decreasing from atmospheric, the data for a particular burner size reveal first an increase of burning velocity, then a decrease with further reduction of pressure. The dashed straight line, therefore, represents the locus of points unaffected by quenching. The inverse effect of quenching with burner size can also be noted from these data. Thus, the smaller the burner size, the higher the pressure at which the

burning velocity for that burner begins to drop off from the straight line locus. The dead space likewise increases for decreasing pressure, the effect of this phenomenon being to give a value of the calculated burning velocity higher than the true value. Hence, at very low pressures the effect of dead space tends to counteract the effect of quenching on the calculated value of burning velocity. As seen in Figure 10 for the 1.25 inch duct, the burning velocity begins to decrease between 200 and 150 mm Hg absolute pressure because of the quenching effect. Between 100 and 80 mm Hg absolute pressure, however, the effect of dead space essentially decreases the effect of quenching (for burning velocity calculated by the area method).

The propane-air results are compared with those of Cullen⁽¹⁶⁾ for the same mixture. Using a burner-area method with burners of 0.375, 0.500, 0.625, and 1.25 inch diameter, he reported the burning velocity to be an inverse logarithmic function of pressure. His envelope of curves, representing the true burning velocity unaffected by burner size, is reproduced as a straight line in Figure 10. It is seen that his values of burning velocity are somewhat lower than the values at corresponding pressures for this report, particularly at atmospheric pressure. However, for atmospheric pressure the value of burning velocity for this report agrees much better with the values reported by Andersen and Fein^(27, 28), using both the burner method with shadow photography and the particle track method, and by Linnett and co-workers⁽⁹⁾, using the cone-apex angle method with schlieren photography.

For this report the slope of the straight line locus of points

unaffected by quenching is -0.13 as compared to -0.16 for Cullen's envelope curve. Also reproduced in Figure 10 is Cullen's envelope curve for ethylene-air, which has a slope of -.13. A straight line of slope -0.25 is drawn to represent the inverse one-fourth power of pressure dependence of burning velocity as predicted by the Tanford and Pease theory. It is readily seen that the propane-air results for this report and the propane-air and ethylene-air results for Cullen's report indicate a pressure dependence of burning velocity which is considerably less than that of the Tanford and Pease theory.

V. CONCLUDING REMARKS

From the results of this investigation, the following conclusions may be drawn: for mixtures of acetylene-oxygen, with or without nitrogen; ammonia-oxygen, with or without nitrogen; carbon monoxide-oxygen and carbon monoxide-air, the burning velocity is independent of pressure. For propane-air mixtures, the burning velocity varies as $P^{-0.13}$. These conclusions are valid provided the burner size is large enough to nullify the effect of quenching.

These conclusions definitely do not support the Tanford and Pease theory that burning velocity varies as $P^{-0.25}$.

REFERENCES

1. Jost, W., "Explosions and Combustion Processes in Gases", McGraw-Hill Book Company, Inc., New York, 1946.
2. Lewis, B., and von Elbe, G., "Combustion, Flames and Explosions of Gases", Academic Press, Inc., New York, 1951.
3. Michelson, W., "Ueber die normale Entzündungsgeschwindigkeit explosiver Gasgemische", Annalen der Physik und Chemie, 37:1, 1889.
4. Gouy, M., "Recherches Photométriques sur Les Flammes Colorées", Annales de Chimie et de Physique, 18:5, 1879.
5. Conan, H. R., and Linnett, J. W., "The Use of Schlieren Photography in Determining Burning Velocities by the Burner Method", Transactions of the Faraday Society, 47:981, 1951.
6. Stevens, F. W., "The Gaseous Explosive Reaction at Constant Pressure. The Effect of Inert Gases", The Journal of the American Chemical Society, 50:3244, 1928.
7. Linnett, J. W., Pickering, H. S., and Wheatley, P. J., "The Soap Bubble Method of Determining Burning Velocities", Transactions of the Faraday Society, 47:974, 1951.
8. Pickering, H. S., and Linnett, J. W., "The Use of Schlieren Photography in Determining Burning Velocities by the Soap Bubble Method", Transactions of the Faraday Society, 47:989, 1951.
9. Gray, K. L., Linnett, J. W., and Mellish, C. E., "Propylene-Air and Propane-Air Mixtures", Transactions of the Faraday Society, 48:1155, 1952.
10. Tanford, C., and Pease, R. N., "Theory of Burning Velocity. II. The Square Root Law for Burning Velocity", Journal of Chemical Physics, 15:861, 1947.
11. Gaydon, A. G., and Wolfhard, H. G., "The Influence of Diffusion on Flame Propagation", Proceedings of the Royal Society, A196:105, 1949.
12. Boys, J. F., and Corner, J., "The Structure of the Reaction Zone in a Flame", Proceedings of the Royal Society, A197:90; A198:388, 1949.
13. Zeldovich, J. B., and Frank-Kamenetski, D. A., "On the Theory of Uniform Flame Propagation", Comptes Rendus (Doklady) de l'Académie des Sciences de l'URSS, 19:693, 1938.

14. Hirschfelder, J. O., and Curtiss, C. F., Third Symposium on Combustion and Flame and Explosion Phenomena, The Williams and Wilkins Company, Baltimore, 121, 1949.
15. Henkel, M. J., Spaulding, W. P., and Hirschfelder, J. O., Third Symposium on Combustion and Flame and Explosion Phenomena, The Williams and Wilkins Company, Baltimore, 127, 1949.
16. Cullen, R. E., "The Effect of Pressure on the Propagation Rate of Bunsen Flames in Propane-Air and Ethylene-Air Mixtures", University of Michigan External Memo, 1950.
17. Culshaw, G. W., and Garside, J. E., Third Symposium on Combustion and Flame and Explosion Phenomena, The Williams and Wilkins Company, Baltimore, 204, 1949.
18. Pickering, H. S., and Linnett, J. W., "The Burning Velocities of Some Ethylene-Oxygen-Nitrogen Mixtures", Transactions of the Faraday Society, 47:1101, 1951.
19. Ubbelohde, L., and Anwandter, R., "Zur Keuntnis der Bunsenflamme im Unterdruck", Journal für Gasbeluchtung und Wasserversorgung, 60:225, 1917.
20. Gilbert, M., "The Investigation of Low-Pressure Flames", C.I.T. J.P.L. Report No. 4-54, 1949.
21. Wolfhard, H. G., "Die Eigenschaften stationärer Flammen im Unterdruck," Zeitschrift für technische Physik, 24:206, 1943.
22. Eriksen, G. A., "Investigation of Flame Velocities at Low Pressures", A.E. Thesis, CIT, 1952.
23. Wheatley, P. J., and Linnett, J. W., "Some Acetylene + Oxygen + Inert Gas Mixtures", Transactions of the Faraday Society, 48:338, 1952.
24. Badin, E. J., Stuart, J. G., and Pease, R. N., "Burning Velocities of Butadiene-1,3 with Nitrogen-Oxygen and Helium-Oxygen Mixtures", The Journal of Chemical Physics, 17:314, 1949.
25. Friedman, R., and Burke, E., "Burning Velocity of Ethylene Oxide Decomposition Flames", Scientific Paper No. 1701, Westinghouse Research Laboratories, 1952.
26. Ausloos, P., and Van Tiggelen, A., "Vitesse de propagation de la flamme dans des mélanges gazeux contenant d'ammoniac", Bulletin des Sociétés Chimiques Belges, 60:433, 1951.

27. Andersen, J. W., and Fein, R. S., "Measurements of Normal Burning Velocities and Flame Temperatures of Bunsen Flames", *The Journal of Chemical Physics*, 17:1268, 1949.
28. Andersen, J. W., and Fein, R. S., "Measurement of Normal Burning Velocities of Propane-Air Flames from Shadow Photographs", *The Journal of Chemical Physics*, 18:441, 1950.

TABLE I

Representative Composition of Commercial Bottled Gases

Acetylene %	Propane %	Oxygen %	Nitrogen %	Ammonia %	Carbon monoxide
C ₂ H ₂ 99.62	C ₃ H ₈ 96 to 97	O ₂ 99.7	N ₂ 99.5	NH ₃ 99.95	CO 96.8%
O ₂ 0.08	C ₂ H ₂ 3 to 2	N ₂ 0.3			CO ₂ 0.36%
N ₂ 0.11	isobutanes and				H ₂ .97%
H ₂ 0.06	heavier 1				N ₂ 1.0%
H ₂ S 0.01					saturated
SiH ₄ 0.03					hydrocarbons 0.8%
CO 0.01					
CH ₄ 0.04					Fe 1.19mg/l
PH ₃ 0.04					S 0.32mg/l
NH ₃ trace					

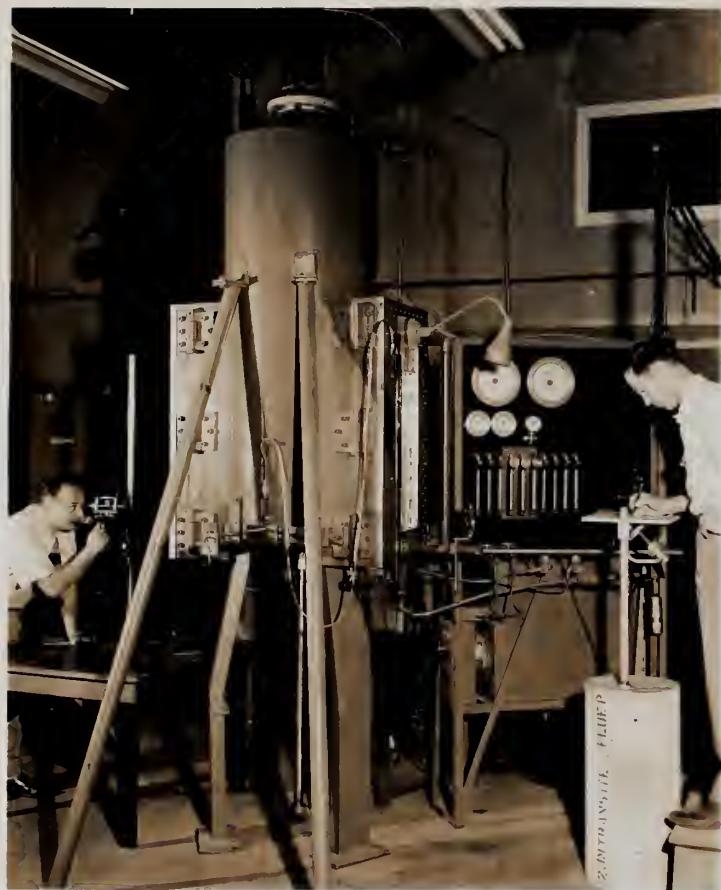


Figure 1. Experimental Setup

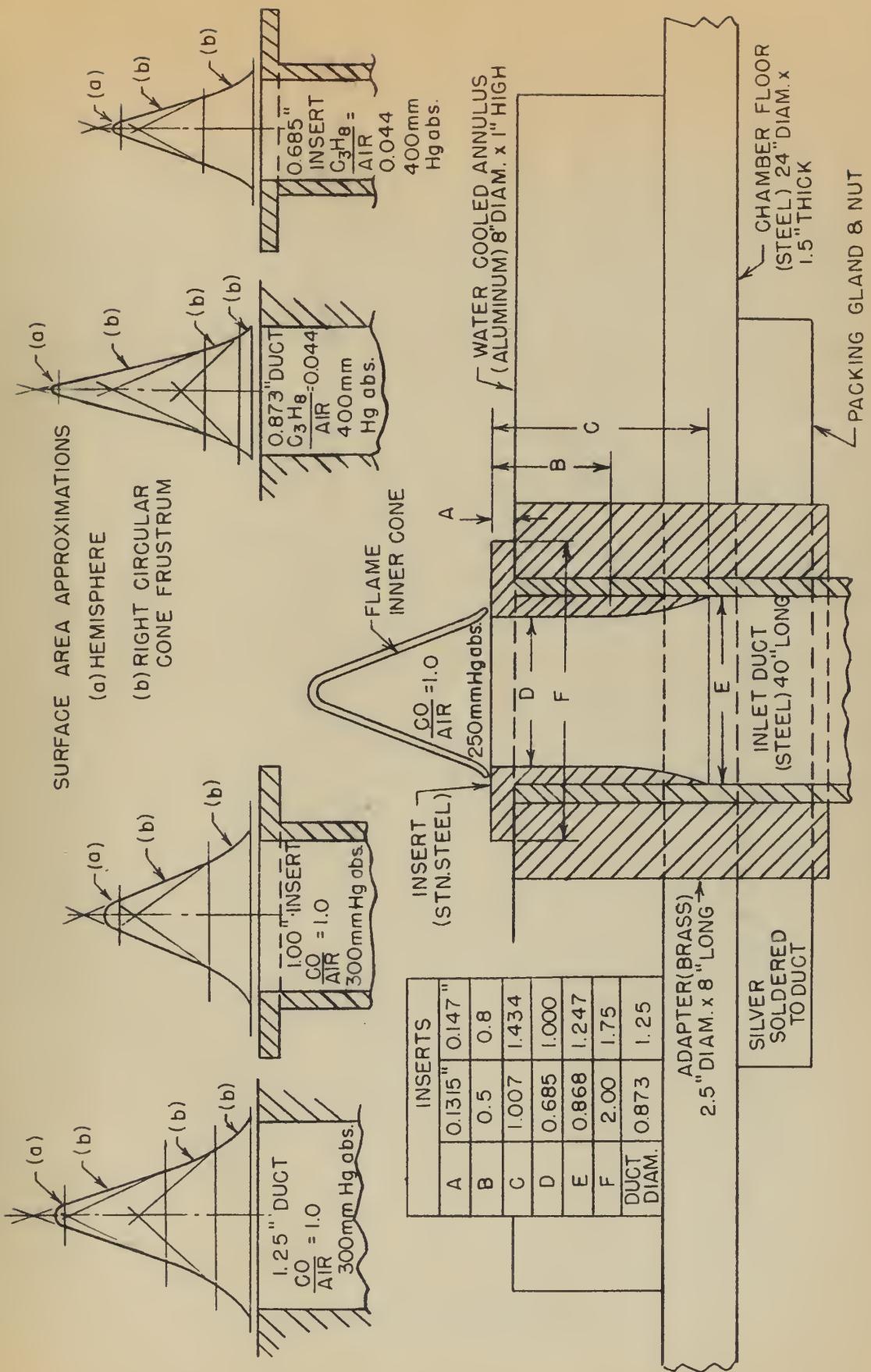
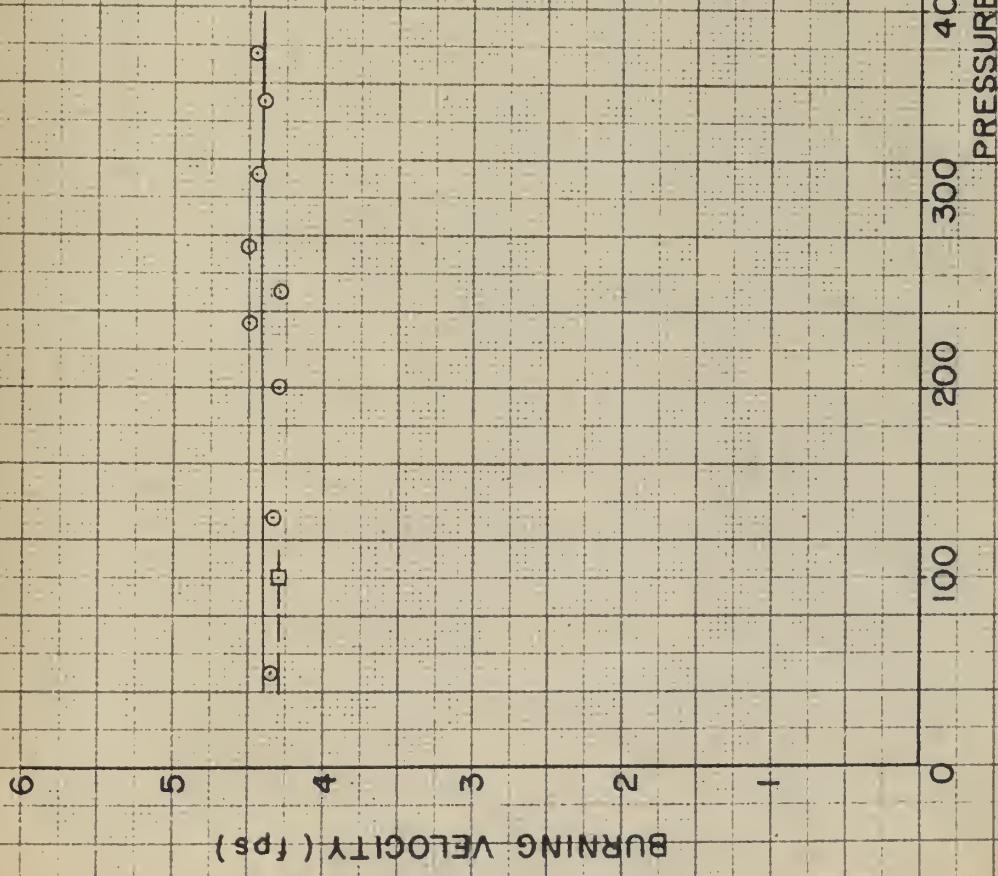


FIG. 2 - BURNER DUCT EXIT,
SHOWING INSERT, TYPICAL FLAMES, AND FLAME AREA APPROXIMATIONS



$$\frac{C_2H_2}{O_2} = 0.056 \text{ (VOL. RATIO)}$$

—○— THIS REPORT, O, 5 IN DUCT
—□— ERIKSEN, (REF. 22) 1.25 IN. DUCT

FIG. 3-ACETYLENE-OXYGEN
VARIATION OF BURNING VELOCITY WITH PRESSURE

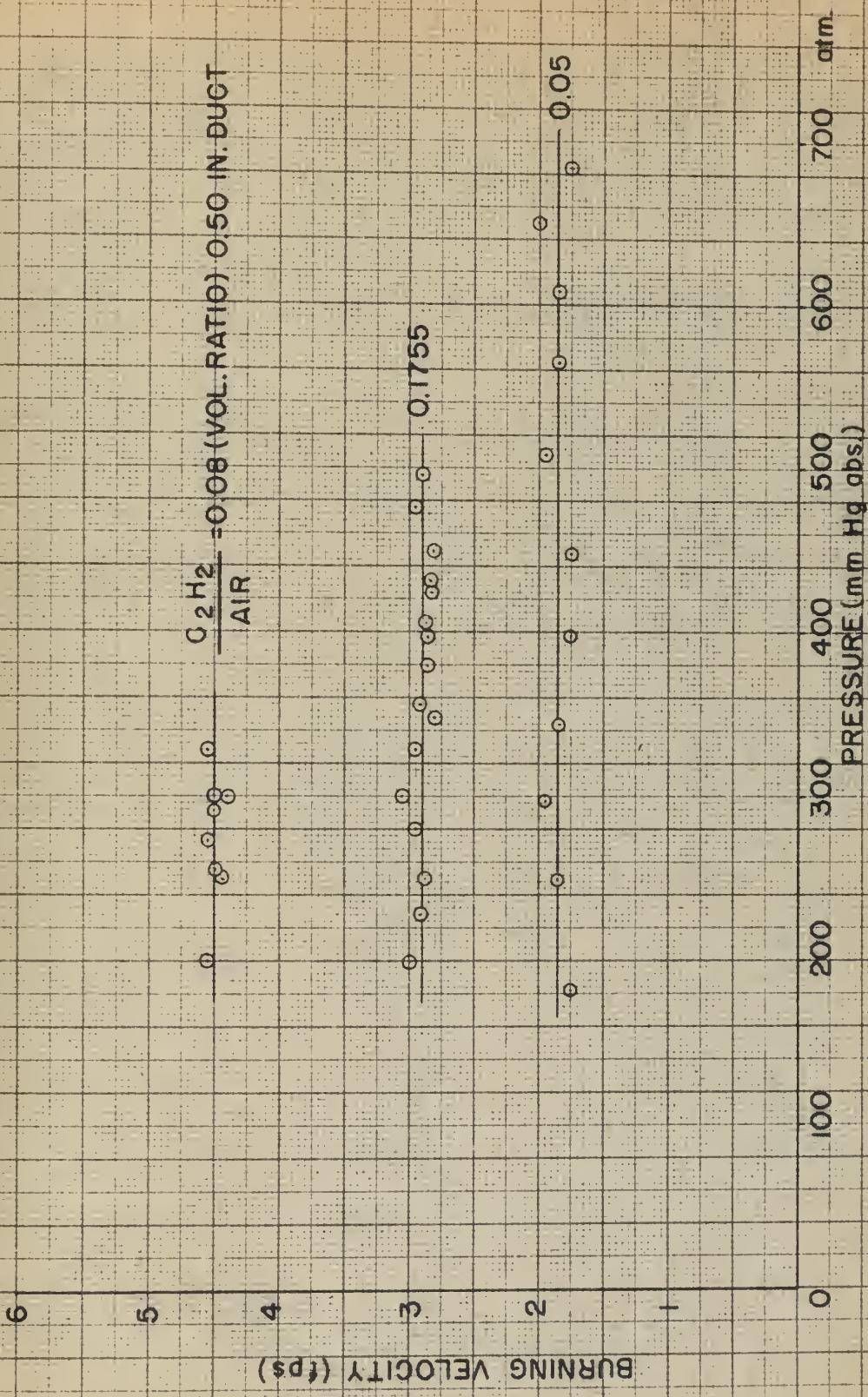


FIG. 4 - ACETYLENE - AIR
VARIATION OF BURNING VELOCITY WITH PRESSURE

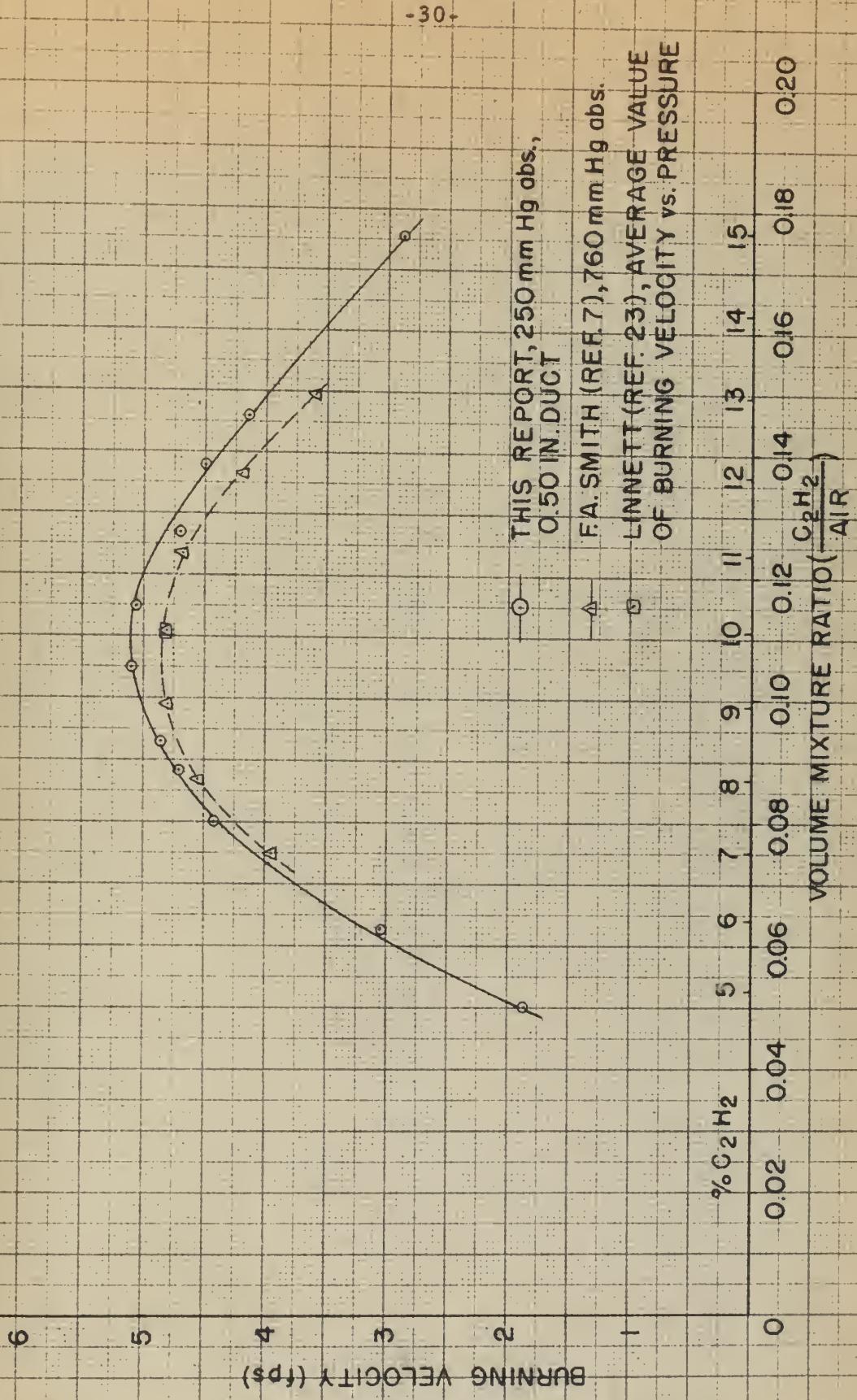


FIG. 5 - ACETYLENE - AIR
COMPARISON OF BURNING VELOCITIES

FIG. 6 - ACETYLENE - OXYGEN - NITROGEN



-31-

BURNER DIAMETERS

- △ 1.25 IN. DUCT
- 0.685 IN. INSERT

$$\frac{N_2}{O_2} = 6.0 \text{ (VOL. RATIO)}$$

$$\frac{C_2H_2}{O_2} = 0.56$$

$$\frac{C_2H_2}{O_2 + N_2} = 0.08$$

BURNING VELOCITY (fps)

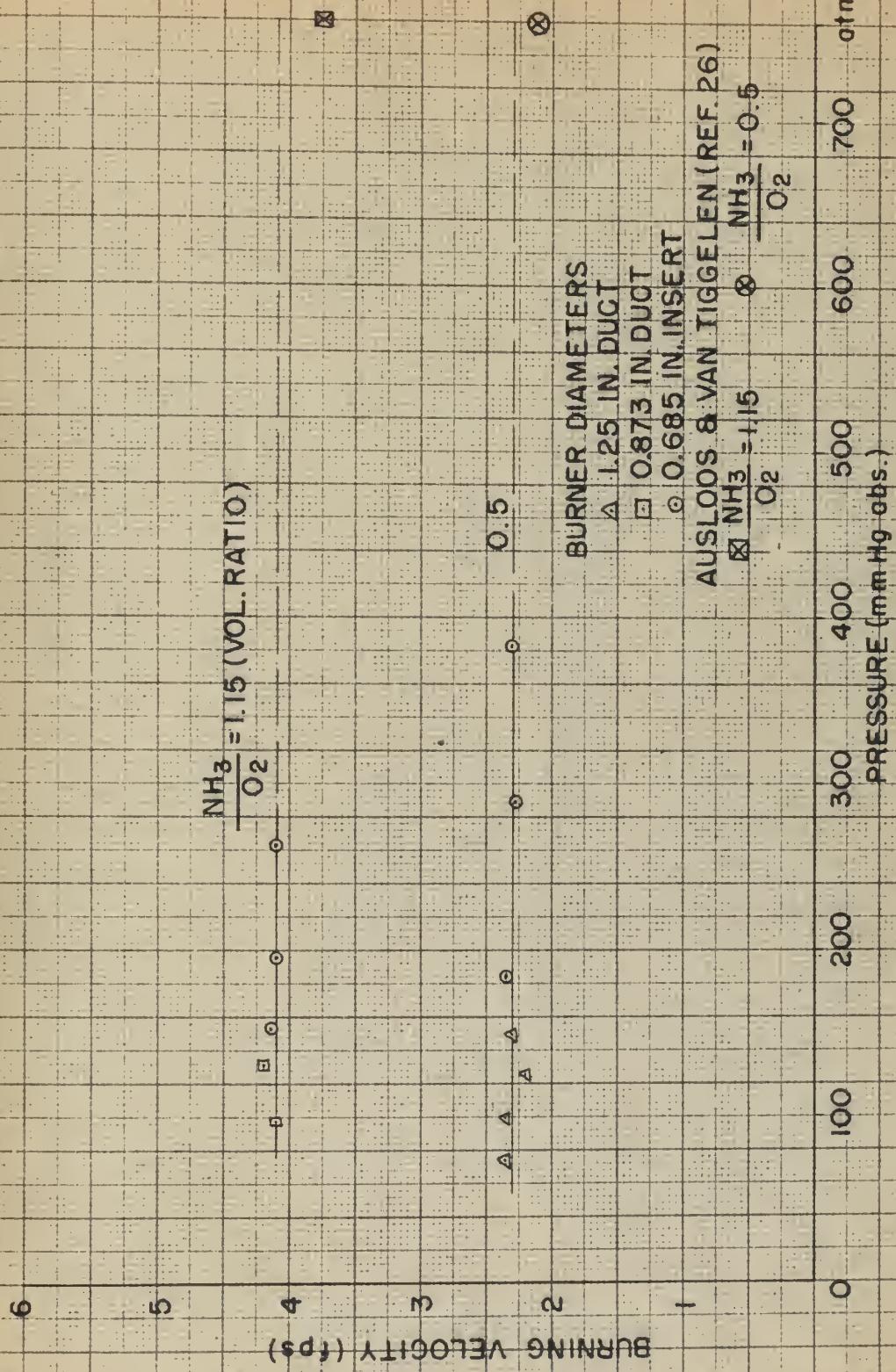


FIG. 7 - AMMONIA-OXYGEN
VARIATION OF BURNING VELOCITY WITH PRESSURE

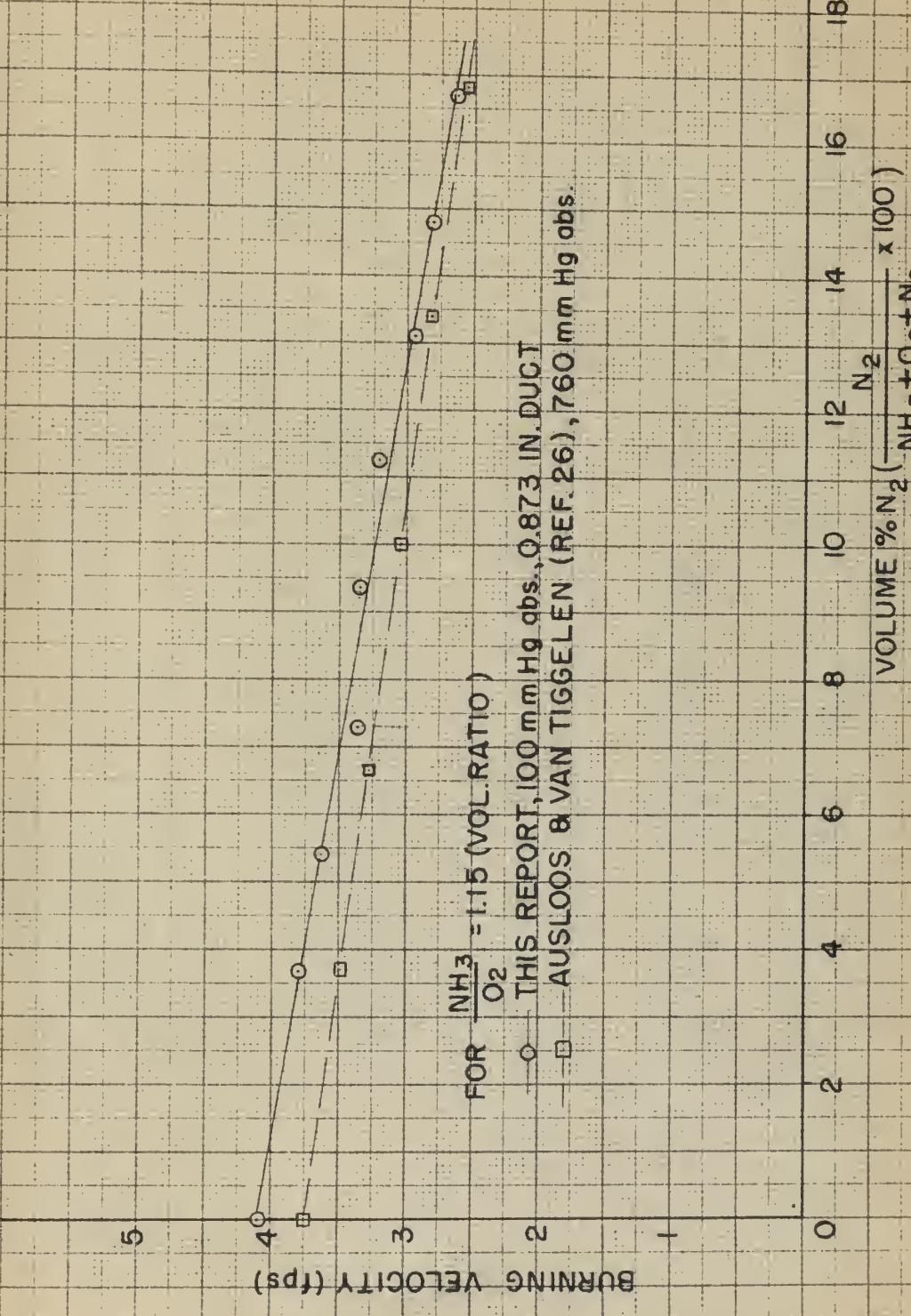


FIG. 8 - AMMONIA-OXYGEN-NITROGEN
COMPARISON OF BURNING VELOCITIES

6 BURNER DIAMETERS

◊ 1.25 IN. DUCT

◊ 1.00 IN. INSERT

□ 0.873 IN. DUCT

• 0.685 IN. INSERT

JAHN (REF. 2)

$$4 \quad \square \quad CO - O_2, CO \text{ CONTAINED } 1.5\% H_2, 1.35\% H_2O \quad \left. \begin{array}{l} CO \\ CO + O_2 \end{array} \right\} = 0.889$$

$$\odot \quad CO - O_2, CO \text{ CONTAINED } 1.35\% H_2O$$

$$O_2 \text{ CONTAINED } 1.5\% N_2 \text{ IN BOTH CASES}$$

$$3 \quad \blacksquare \quad CO - AIR, CO \text{ CONTAINED } 1.5\% H_2, 1.35\% H_2O \quad \left. \begin{array}{l} CO \\ CO + AIR \end{array} \right\} = 0.5$$

$$\otimes \quad CO - AIR, CO \text{ CONTAINED } 1.35\% H_2O$$

$$2 \quad \frac{CO}{CO + O_2} = 0.889 \text{ (VOL. RATIO)}$$

BURNING VELOCITY (cm/s)

-34-

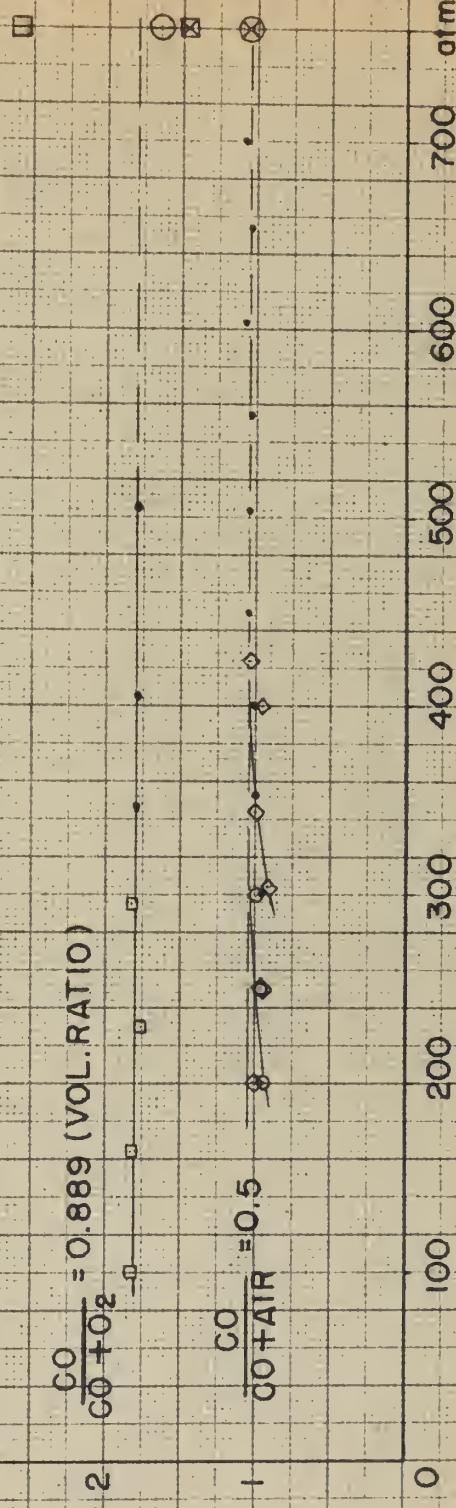


FIG. 9 - CO - O₂ & AIR

VARIATION OF BURNING VELOCITY WITH PRESSURE

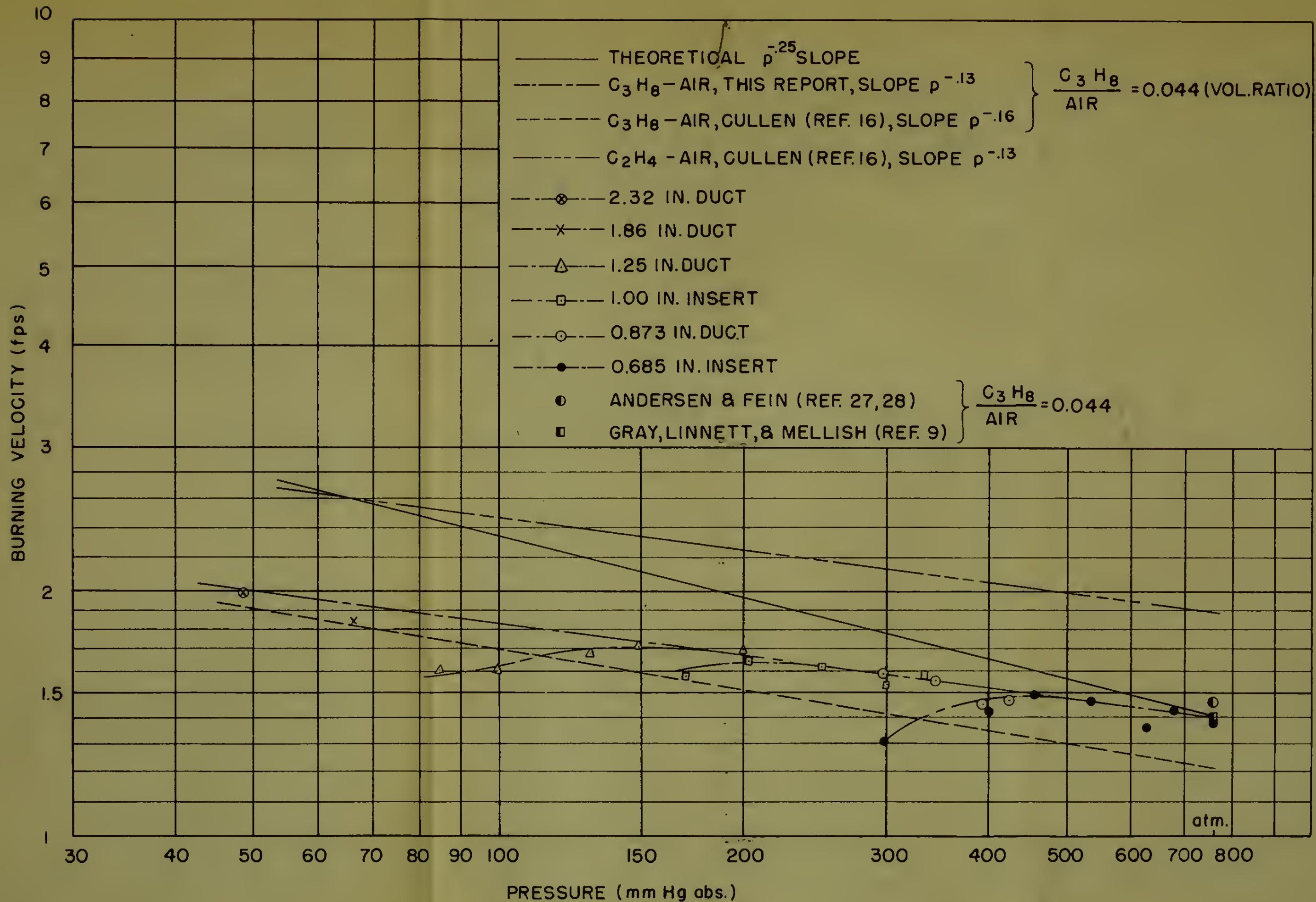
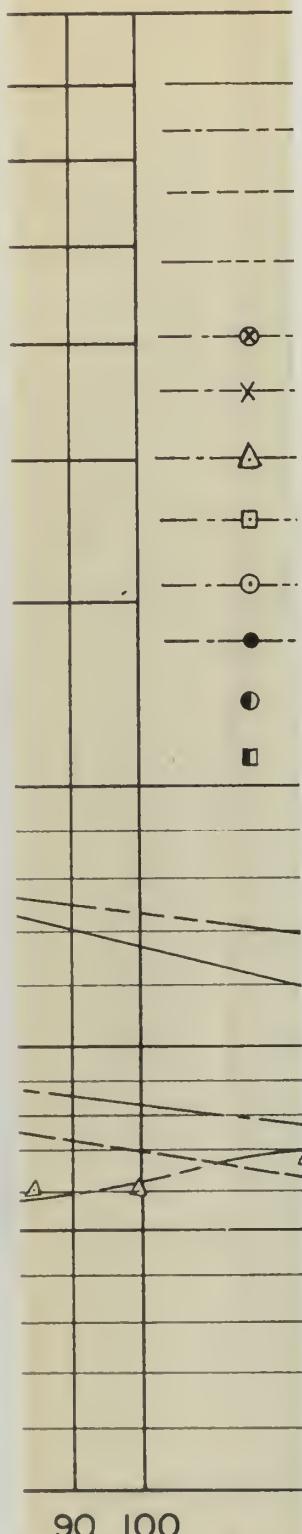


FIG. 10 — PROPANE — AIR
VARIATION OF BURNING VELOCITY WITH PRESSURE



PRESSUF

FIG. 10 — PROP.
OF BURNING V

JUL 2
DEC 31
DEC 31

BINDERY
4164

Thesis
P15 Pardee **20546**
Variation of burning velocity
with pressure.

Bind
BINDER

6

Thesis
P15 Pardee **20546**
Variation of burning velocity
with pressure.

-

Library
U. S. Naval Postgraduate School
Monterey, California



thesP15
Variation of burning velocity with press



3 2768 001 97180 7
DUDLEY KNOX LIBRARY